AN APPRAISAL OF MATERIALS OF CONSTRUCTION FOR USE IN NAVAL STRUCTURES

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by

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FOREWORD

In the field of structural design the engineer normally limits himself to a relatively narrow selection of materials for utilization in the body of a structure. Apart from consideration of the properties of the structural material, the selection is often dictated by such factors as building code restrictions, "standard" practice, and the personal preferences of the designer. In a large measure these latter factors stem not from any marked superiority of one material over the others, but from prejudice, resistance to change, and facility of design technique.

To become fully conversant with the properties of all potential materials of construction is an exhaustive task; hence it is natural for the engineer to investigate only those construction media of most widespread use. However, such a tendency can only lead to a stagnation of materials development, and the engineer has a further responsibility to give due consideration to all prospective structural materials.

To assist the designer in filling this responsibility, there is compiled on the following pages a discussion of the merits and limitations of several materials which may have a future in the structural field. It is not the intention of this paper to provide a design manual for the

use of these materials. Rather, this compendium is designed to give the engineer the information necessary for selection of a structural material to fit the needs of his particular problem, and to provide a bibliography for further, more complete investigation of the material so selected.

Not all of the materials herein discussed are new; many of them have been used extensively outside of the field of building construction, and others, once prominent as structural media, have fallen into virtual disuse. At the present stage of development, some of the materials discussed hereafter may seem useful only for "special purpose" items; however, by such specialized use of the product, the engineer becomes more familiar with the material and more bold in using it. Thus materials technology is advanced.

It should not be forgotten that less than a century ago a French gardener was puttering around with a special material for flower pots. That material turned out to be reinforced concrete.

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CHAPTER I

PROBLEMS OF DETERIORATION OF CONVENTIONAL CONSTRUCTION MATERIALS

To establish the desirability for broadening the field of structural materials, it is first necessary to dwell briefly on the more usual materials of construction. While the familiar properties of strength, weight, and appearance all are important factors to be considered, the less commonly known characteristics which may ultimately influence the choice of materials are those of durability. Perhaps in no phase of structural design does durability weigh more heavily than in the field of maritime construction, for the pounding waves, corrosive waters, drifting sands, and salt-laden air serve to increase the tempo of nature's destructive attack.

Traditionally the materials for waterfront construction have been earth, stone, wood, concrete, and steel. The shortcomings of these materials have been treated at great length by many writers. The essence of these treatises is briefly summarized in the following paragraphs.

Earth, or soil, is the most commonly occurring of all structural materials. However, in defiance of this ubiquitous occurrence, soil is perhaps the most complex of structural media. By modern methods of soil mechanics the age-old arts of earth dike and dam construction are being rationalized and

improved. Nonetheless, in earth structures the specified soil condition is usually a transitory thing at best, being predominantly subject to fluctuations in moisture content which may or may not have been foreseen. To illustrate: earth dams or reservoir walls with cores of highly colloidal cohesive soil may fail following prolonged dry spells. During periods of drought, with attendant lowering of the level of impounded water, the impervious cores may dry out, shrink, and crack to such a degree that when the water level is again raised, the structures will leak profusely. Furthermore, without protective surfacings of some sort, soil structures are particularly vulnerable to the erosion of wind, wave, and rivulet.

As a material to resist the impact of pounding waves, stone has few equals. However, the weight which serves stone so well as a breakwater material can also be its nemesis, for, particularly with undressed stone, the high bearing pressures developed may cause the stone to sink into soft soils. In most cases, though, this difficulty can be surmounted by placing a foundation mat of sand to spread the load. A less commonly realized failing of stone is the fact that even good dense rock will slowly corrode in sea water.(33)* Because of this corrosion even the most carefully constructed masonry seawall or breakwater will gradually loosen up. After this

*Number in parentheses indicates reference listed in bibliography.

initial looseness sets in, wave action will cause working of the rocks with consequent abrasion, and the structure will eventually loosen up sufficiently to cause failure.

Of a more facile nature is wood--light in weight, reasonably strong, and quite widely available. Despite wood's ageless popularity as a structural material, the shortcomings to its use have yet to be overcome. Kept dry, wood is highly combustible; wet, it becomes very durable, but its strength is somewhat diminished. Alternate wetting and drying accelerates rotting. Because of its organic nature, wood is an attractive food source for any number of destructive flora and fauna. Fungi, termites, and beetles attack wood on land. A timber pile standing in open water may be riddled by marine borers at one end and by woodpeckers at the other. The attempts to combat these difficulties are myriad. Fireproofing and fire-retarding processes are available, but their record of performance is spotty. Fireproof and vermin-proof casings have been successfully applied to wood, but their use considerably increases structural costs. Various toxic coatings or impregnations such as coal tar creosote or pentachlorophenol have been used with varying degrees of success against biological attack. In locales where this attack is particularly severe, such treatment may appreciably prolong the life of timber structures. However, in areas where timber normally deteriorates very slowly, it is quite possible that the toxic

effects of these chemicals would be dissipated within the normal lifetime of the structure.(33)

Reinforced portland cement concrete has decidedly outgrown the flowerpot in which it was nurtured. However, despite continually improving concrete technology and the codification of design technique, there still remain many drawbacks to be overcome. As if to belie its popularity for use in maritime structures, concrete behaves most poorly in marine environments.(33)

Even very dense concrete is not impervious to moisture. In areas where freezing can occur, the expansion on freezing of the percolated water will cause spalling of the concrete. Likewise, in the zone of wetting and drying, a similar action occurs as dissolved salts crystallize from evaporating sea water which has permeated the concrete. Furthermore, the sodium-magnesium sulphates in sea water have a particularly deleterious corrosive effect upon concrete.(33)

If a seawall or breakwater is constructed of discreet concrete units, the above types of deterioration can lead to a structural failure similar to that hypothesized for stone structures.

If the concrete is not to be immersed, air-entraining cements offer improved resistance to freezing-thawing deterioration and to chemical corrosion. However, because of its greater porosity and consequent higher permeability under pressure heads, air-entrained concrete is not particularly suited for structures which may be submerged. (33)

A rather unexpected phenomenon, and one for which no satisfactory solution has been found, is the occasional attack upon concrete by the pholad, a type of boring mollusk resembling a small clam, which, shell and all, gouges its way into the concrete. However, this type of attack occurs so infrequently that it need be considered only in those locales where pholadiae are known to be extremely active.(33)

When steel reinforcing is added to the concrete, the material becomes even more vulnerable to marine exposure, for to the difficulties of concrete deterioration are added the problems of steel corrosion. These latter problems will be more fully treated in later paragraphs. At this juncture, suffice it to say that cracking of the concrete exposes the steel to the corrosive medium. If the nature of the steel corrosion is such that the corrosion product builds up on the surface of the metal, this build-up can create sufficient pressure to cause spalling of the concrete and further exposure of the steel. Since the steel normally carries a goodly portion of the load in reinforced concrete structures, the seriousness of steel corrosion can readily be appreciated. The use of concrete pre-stressing techniques is one of the more effective means of combating the problem of cracking.

The development of modern welding and cutting techniques has contributed immensely to the versatility of steel as a structural medium, and, particularly when a certain amount of

field improvisation is contemplated during the course of a construction project, this versatility may well lead to the selection of steel in preference to other materials. However, should the proposed structure be subject to exposure to salt water or to sea air, the designer should carefully weigh the corrosive effects of these media before selecting a structural material.

In the succeeding paragraphs, the subject of corrosion of steel will be treated in general terms, for a precise discussion would be quite lengthy and is not necessary for appreciation of the problem.

Structural grade steels, as are most metals, are subject to a variety of corrosion phenomena. Corrosive actions may be categorized as chemical and electro-chemical, although the end-product of corrosion may be the same in either case. Basically, chemical corrosion refers to the destruction of a metal by direct combination of elements or compounds to form the corrosion products. Electro-chemical corrosion is that which results from a current flow between anodic and cathodic areas, corrosion occurring at the anode. The electrical potential may result from the immersion of dissimilar metals in an electrolyte, or, because of variations in the surface composition of a metal, a similar potential may be set up on the surface of a single metal.(33,43,64)

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If the corrosion product (most commonly rust in the case of steel) is deposited on the corroding surface, this product may form a protective surface film which may retard or completely prevent further corrosion. Should this film be destroyed, or if the corrosion product is not deposited on the metal, the rate of corrosion will be undiminished, all other conditions remaining unchanged. The protective coating may be damaged by physical erosion, by chemical attack by various solvents, or by metabolic products of biological organisms.(64)

Protective surface films may be applied artificially by painting or by applying bituminous or metallic coatings; if the metal is to be permanently submerged, coverings of this sort can offer only very temporary protection. Encasing the steel in concrete is a more expensive but more permanent means of providing surface protection.(33)

To prevent electro-chemical corrosion of steel,cathodic protection is gaining widespread acceptance. Quite simply, this method deters corrosion by making steel the cathode in the electrical circuit. This can be accomplished by imposing a direct current or by installing in the circuit a sacrificial anode of a more active metal, commonly magnesium or zinc.(33,64

The foregoing comments serve to indicate that the conventional structural materials in common use today are far from perfect. Most of their shortcomings can be overcome, but in many cases the methods of so doing are very stringent and

rather costly. Ideally, new materials should be cheaper, stronger, and more durable than the aforementioned. Of the materials treated in the following chapters, this, unfortunately, is not necessarily so. However, if the designer(and ultimately the financor) can accept the principle of assigning proper values to such intangibles as esthetics, elimination of strenuous maintenance procedure with its inevitable element of human error, and experiment for the sake of experiment, purely monetary comparisons may be outweighed. And only through wide usage of new materials can their costs be reduced.

Recommended Reading for More Detailed Discussion of Information Summarized in Chapter I:

Greathouse, G.A., and Wessel, C. J., "Deterioration of Materials, Causes and Preventative Techniques." Reinhold, 1954, 835 pp.

"The Corrosion Handbook," Edited by Uhlig, H. H., John Wiley & Sons, 1948, 1188 pp.

CHAPTER II

STAINLESS STEELS AND LIGHTWEIGHT METALS

Among the ten most plentiful elements are the metals aluminum, iron, magnesium, and titanium, comprising respectively 7.5, 4.7, 1.9, and 0.58 per cent by weight of the earth's crust.(28) A further fortunate coincidence is the fact that each of these materials possesses certain properties desirable in structural metals. However, the development of these metals has depended not upon their mineralogical abundance, but rather upon devising means of producing the materials in quantities of economic significance.

Although the manufacture of iron is a very old art,having been practiced among the oldest civilizations, not until the latter half of the last century were process controls and production methods developed for the quantity manufacture of structural grade steels of uniform quality.(28) These steels, essentially of the low carbon or mild types, are now so commonplace that their use is virtually second nature to the structural engineer. Nonetheless, these steels may deteriorate rapidly in certain environments, and the designer is then faced with the choice of providing protection for the steel or selecting a more durable material.

Steel metallurgists early recognized the hardening effect of chromium alloyed to steel. However, not until the turn of

the century was the improved corrosion resistance of chrome steels established. Since that time the development of the so-called "stainless" and "corrosion-resistant" steels has proceeded rapidly.(77)

Before discussing the properties of the various stainless steels it might be wise to review briefly the metallurgy of the plain carbon steels. Pure iron, on equilibrium cooling, has two stable crystallographic forms. Iron freezes at 2802°F as body centered cubic delta iron; at 2552°F the atoms reorient themselves to the face-centered cubic gamma iron; while at 1670°F a reshuffling to body-centered cubic alpha iron occurs. Alpha and delta iron are designated as ferrite, and gamma iron is classified as austenite. The effect of carbon, when added to the iron to form steel is to increase the range of stability of austenite. In the mild steels austenite is stable down to 1333°F. Low carbon steels which have cooled slowly to room temperature consist of a mixture of ferrite and cementite (iron carbide). However, in the austenitic range pure carbon is dissolved interstitially in the gamma lattice. When the cubic structure shifts from face-centered to body-centered, an expansion takes place; if, however, the austenite is quenched, the reorientation starts at a very rapid rate, and the carbon and iron atoms become jammed up so that the expansion to alpha iron cannot transpire. The resulting structure is the very hard, internally stressed

martensite. Subsequent heat treatment of martensite is required to relieve some of the internal stress.(24,48,61,76)

Essentially the stainless steels are those containing from 12 to 30 per cent chromium; carbon contents may be as high as 1.2 per cent, and varying quantities of other alloying elements, principally nickel, may be added.(6,77)

The effect of chromium is to derease the range of stability of austenite. Conversely, the addition of nickel may so extend this range that stable austenite can exist at room temperature. Stressed structures such as martensite cannot result from quenching pure iron-chrome or iron-nickel alloys, for the foreign atoms directly replace iron atoms in the cubic lattice rather than being interstitially contained.(77)

From the foregoing it becomes apparent that the properties of the various types of stainless steels are a result of the ultimate balance of effects of the carbon, chromium, and nickel on the austenite range. Because of their behavior on quenching, the stainless steels are classified in three categories: Class I, the martensitic or hardenable steels; Class II, the ferritic or non-hardenable steels; and Class III, the austenitic steels.(77)

As might be surmised, the Class I steels are Fe-Cr-C alloys so proportioned that the austenitizing effect of the carbon dominates the ferritizing effect of the chrome to such a degree that martensite is formed upon quenching from

the gamma range. Conversely, in the Class II steels the chromium is dominant, and so little austenite is formed that quenching does not produce significant martensitic hardening. The Class III stainlesses are Fe-Cr-Ni-C alloys containing sufficient nickel and carbon to permit the existence of austenite at room temperatures. Cobalt and manganese have the same effect as nickel but are less commonly used.(77)

Although the corrosion resistance of stainless steels is directly proportional to the chromium content, not all chrome steels are stainless. Up to about 12 per cent chrome the steels are known simply as chrome steels; while these alloys have better corrosion resistance than the plain carbon steels, the principal function of the chromium is to impart greater hardness to the metal. In the range of 12-20 per cent chrome fall the corrosion resistant steels. These metals are sufficiently passive to be almost non-corrosive in mildly corrosive media. In the maximum commercial range of 20-30 per cent chrome fall the non-oxidizing stainless steels. These steels are virtually non-corrosive in even the strongest oxidizing environments.(77)

Sulphuric acid seems to straddle the line between those acids which oxidize the metal and those which reduce the oxidation product. Stainless steels have excellent resistance to nitric acid and variable to good resistance to sulphuric acid depending on the presence of oxidizing salts. However,

the nemeses of the stainless steels are the halide ions, and the metals perform poorly in hydrochloric acid and in solutions of the halide salts. This explains the fact that the stainless steels do not perform particularly well in sea water; the addition of molybdenum improves the resistance to marine environments, but still the metal should be used with discretion if such an exposure is contemplated. The non-oxidizing steels are virtually inactive in air, but in sea air or in industrial atmospheres containing halide ions significant corrosion can occur. In sulphurous atmospheres discoloration may result.(64,77)

In the ensuing discussion of physical and mechanical properties of stainless steels only the wrought alloys will be discussed inasmuch as the cast steels have very limited structural application. For tabular and graphical presentation of the properties of these steels and other materials discussed in this dissertation see the appropriate appendix.

The Class I and Class II steels have very similar physical characteristics. Each has a specific gravity of 7.8 and is ferro-magnetic at room temperature. The metals melt at about 2700°F; their specific heats are essentially that of mild steel; the coefficients of thermal expansion are only slightly lower than for mild steel. On the other hand, the heat conductivity of these metals is markedly lower and the electrical resistivity is significantly higher than the

corresponding properties of structural grade steels. The combination of low heat conductivity and high electrical resistivity makes the resistance welding of the stainless steels a highly efficient process. However, the slow conduction of heat away from the weld area might cause heat concentrations sufficient to create undesirable metallurgical effects in the base metal. The stainless steels have a reflectivity of approximately 60-65 per cent -- a brightness equal to that of platinum.(77)

The Class I steels contain 0.15-1.20 per cent carbon and 11.5-18.0 per cent chrome, the higher carbon contents corresponding to the higher percentages of chromium. As a general rule the tensile strength and hardness increase with increasing chrome content while the ductility and impact strength correspondingly decrease. A very sharp drop in the impact resistance occurs when the chromium content exceeds 16 per cent. The elastic tensile moduli of the martensitic steels are practically those of the structural steels. In the fully annealed condition the ultimate tensile strengths of these steels range from 70,000 to 105,000 psi with yield strengths of 50-60 per cent of these amounts. Brinell hardnesses vary from 135 to 250 while Izod impact values range from 110 ft-lb for the low chrome alloys to 5 ft-lb for the high chrome steels.(6,77)

The outstanding feature of the Class I steels is their hardenability when quenched from the austenite range. When the medals are fully hardened the ultimate tensile strengths are increased to the range of 200,000 to 285,000 psi with yield strengths increasing to 75-95 per cent of these figures. Brinell hardness now varies from 380 to 620. As might be expected, impact strength and ductility drop sharply, and the new Izod range is 45 to 2 ft-lb. The highly hardenable steels are seldom used in the fully hardened condition because impact resistance and ductility are so low that the metals become undependable in service. For this reason stress relieving treatments are required which may reduce the full hard properties by 10 per cent.(77)

Because of their comparatively low chrome contents the Class I steels are less expensive than the other stainless steels; however, this reduced cost is attained at the expense of corrosion resistance. These steels do have an extremely good resistance to nitric acid, though, and consequently are the logical economic choice when this resistance is the dominant factor. Because of their brittleness in the hardened condition their structural application is quite limited. Furthermore, the hardened martensitic steels are extremely notch sensitive, so any design embodying these alloys should avoid grooves, notches and bends which might cause undue stress concentrations.(77)

The Class II steels contain 0.08 to 0.35 per cent carbon and 11.5 to 27.0 per cent chromium. As a class the ferritic structure of these steels is so preponderant that martensitic hardening does not occur. There are moderate exceptions to this rule, but the slightly hardenable Class II steels will be neglected in this discussion. On the whole the Class II alloys offer such poor mechanical properties that only their superior corrosion resistance can justify the expense of their use. The tensile modulus of these steels does not vary appreciably from that of the mild steels; the ultimate tensile strengths increase with chrome content from 60,000 psi to 80,000 psi. Yield strengths vary from 35,000 to 50,000 psi. Brinell hardness ranges from 130 to 185. Because of the dominance of chrome, the Izod impact strengths of these alloys are very poor, grading from 35 ft-lb down to a minimum of one ft-lb for the extremely high chrome steel. In view of these low impact values, widespread structural use of these metals is quite impracticable.(6,77)

The Class III steels are probably the most distinctive and the most clearly defined of the stainless steels. These metals, containing 0.08-0.25 per cent carbon, 16-26 per cent chromium, and 6-22 per cent nickel, are characterized by the presence of austenite at normal temperatures. In this class fall the familiar 18-8 stainless steels (18% chrome - 8% nickel), and the remainder of the alloys in this class are,

to all intents and purposes, merely modifications of the 18-8's. From the standpoint of maritime construction the significant austenitic steels are the 18-8's with molybdenum added for greater resistance to the chloride ion.(77)

In physical properties the austenitic stainless steels are decidedly different from the Class I and Class II steels. Their specific gravity is 8.0. Because of their austenitic structure, the annealed Class III steels are non-magnetic; however, on cold working the resulting structural changes will induce ferro-magnetism in direct proportion to the degree of working. The melting temperature of these alloys is reduced to approximately 2600°F. The coefficients of thermal expansion of these metals are approximately one and one-half times that of mild steel; this factor can lead to appreciable dimensional instability during welding operations. The specific heats of the austenitic steels may be as much as 25 per cent greater and the thermal conductivities 50 per cent less than corresponding properties of structural steel. Furthermore, the electrical resistivities of the Class III steels are about 10 per cent greater than that of plain carbon steel.(77)

The mechanical properties of the austenitic steels exhibit a surprising uniformity and seem virtually independent of the constitution of the alloy. The moduli of elasticity of the annealed steels are essentially that of the mild

steels. The ultimate tensile strengths range from 80,000 to 100,000 psi with yield strengths of 40-50 per cent of these figures. Brinell hardness varies from 140 to 185 while Izod impact values are between 70 and 110 ft-lb.(6,77)

The effect of cold working on these properties is very marked. Elastic moduli are reduced to 22,000,000-25,000,000 psi. Ultimate tensile strengths are dramatically increased to 200,000-350,000 psi, and yield strengths increase to 85-90 per cent of these values. Hardness on the Brinell scale is increased to 200-500. Stress relieving of the work hardened austenitic steels not only improves the tensile strength, yield strength, and proportional limit, but in addition does not incur the simultaneous decrease in ductility expected in other work hardened and stress relieved steels.(6,77)

In addition to their superior corrosion resistance and excellent mechanical properties, the annealed Class III steels have very high impact resistance at sub-zero temperatures. Furthermore, tensile and yield strengths increase as the temperature decreases, while ductility is little affected. The 18-8 steels are also among the best of the heat resisting metals, retaining 50 per cent of their strengths up to about $1200^{\circ}F$.(7,46,60,77)

It is quite apparent that the austenitic stainless steels offer numerous possibilities for structural application. The material is used for building facings, framing, and trim, and

is gaining increased use in "sandwich panel" types of curtain wall construction.(45,77)

In exterior architectural treatments with stainless steel, the lack of maintenance required for the metal, as well as its pleasing appearance, should compensate in part for the additional cost of the material. However, the discoloring effect of sulphurous atmospheres as well as the corrosive tendencies of marine atmospheres should be weighed before specifying a stainless steel facade. Furthermore, because of its high reflectivity, irregularities in the surface of a stainless steel panel cause very noticeable optical distortion; therefore, extreme care is necessary in mounting stainless steel sheets and panels to prevent undue warping and bending.(45)

The newest of the common metals and perhaps the greatest competitor of steel in the structural field is aluminum. Although aluminum is the most common of all metals and is the third most abundant element, not until 1825 was the metal separated from the ore. Most of the aluminum produced today is refined by dissolving aluminum oxide in molten cryolite and reducing the ore by electrolysis.(28,57)

Pure aluminum solidifies at 1220°F into a face-centered cubic lattice. The specific gravity of the metal is 2.7, and in most aluminum alloys this is not appreciably changed. Aluminum is extremely soft and weak with a yield strength of about 7000 psi. However, by the addition of alloying elements,

principally copper, magnesium, and silicon, the mechanical characteristics are so improved that by work hardening and heat treating ultimate strengths of 100,000 psi may be obtained.(6,28,48,61)

Because the solid solubility of copper or magnesium in aluminum decreases markedly with decreasing temperature, there is a tendency for these alloying metals to precipitate out at the grain boundaries during equilibrium cooling. By heating the alloy into the range of high solubility and then quenching, the alloying elements are more uniformly dispersed through the aluminum crystals. The alloying agents will still tend to precipitate, even at room temperatures, but this precipitation now occurs within the grains rather than at the boundaries. To accelerate this intra-granular precipitation the metal is reheated to a temperature below the solubility range. These types of heat treating are known respectively as solution heat treatment and precipitation heat treatment. The mechanical effect of the intra-granular precipitation is to key together the slip planes within the crystal, thus imparting greater resistance to deformation. The ultimate results of these phenomena are greater strength and hardness and poorer ductility and workability.(6,48,76)

Pure aluminum readily forms a protective oxide coating which renders the material quite corrosion resistant so long

as the coating remains intact. Nonetheless, the metal is extremely active in the electro-chemical replacement series,and great care must be taken to prevent electrical contact between aluminum and more noble metals or their salts. Thus it can be surmised that the poor corrosion resistance of the aluminum-copper alloys to sea water probably results from the large electrical potential between these two metals; contrariwise, aluminum-magnesium alloys perform well in marine environments because of the proximity of the two metals in the electro-chemical series.(64)

The wrought alloys of aluminum are numerous and of widely varied composition. Two of the alloys which are rather typical and have good potentialities for structural use are the 17S and 24S groups.

The 17S alloys are probably the most common of the structural aluminums, being available in a wide selection of rolled shapes, plates, and sheets. The dominant alloying constituent is approximately 4 per cent copper with less than one per cent each of manganese and magnesium. In the fully annealed condition the ultimate tensile strength of this alloy is 26,000 psi with yield at 10,000 psi; Brinell hardness is 45. With proper heat treatment the strength of the metal is increased to 62,000 psi and the yield point moves up to 40,000 psi, while hardness is increased to 105. The yield strength of the material decreases rapidly at temperatures

above 300°F. From a structural viewpoint one of the worst features of the 17S alloy is the fact that welding of the heat treated metal reduces mechanical strength and corrosion resistance in the vicinity of the weld, making riveted or bolted construction preferable. As might be expected, 17S, being a cuprous alloy, has poor resistance to sea water. However, by applying a coating of nearly pure aluminum (such metals are designated "Alclads"), the alloy is rendered virtually immune to marine corrosion.(2,6,49,60)

One of the most common alloys used in aircraft construction is 24S, usually fabricated in plates or sheets or in extruded or drawn shapes such as bars or wires. This is also a cuprous alloy with about 4.5 per cent copper, 1.5 per cent magnesium, and 0.6 per cent manganese. Fully annealed properties are: ultimate strength, 27,000 psi; yield strength, 11,000 psi; Brinell hardness number, 42. By proper combinations of heat treatment and cold work these respective properties may be increased to 73,000 psi, 57,000 psi, and 130. Moreover, with aluminum clad 24S sheet, the yield strength may go as high as 66,000 psi. As with 17S, the yield strength of 24S drops rapidly as temperature increases above 300°F. The welding and corrosion resistant propensities are similar to those of 17S.(2,49,60)

In addition to use in building facings and sandwich panel curtain walls, aluminum is being used increasingly in heavy

construction when reduction of dead load becomes of importance. The significance of this dead load reduction can be illustrated as follows: the largest aluminum structural shape listed in the handbook is a 12-inch I-beam weighing 18 pounds per foot; assuming similar working stresses for both steel and aluminum, the lightest steel member having a commensurate bending strength would be a 12WF40 weighing more than twice as much as the aluminum member. However, when designing with aluminum, the engineer must be particularly wary of excessive deflections; because of the low modulus of elasticity of aluminum (10,500,000 psi), an aluminum structure will deflect almost three times as much as an identical steel structure under similar conditions of load.(2,3,28)

The lightest of the common metals is magnesium, with a specific gravity of 1.74. Although almost 150 years have elapsed since the metal was first isolated, not until World War II did the production of magnesium attain significant proportions. The metal is found in a variety of ores, but the most important commercial source of magnesium in the United States is the magnesium chloride of subterranean brines in Michigan.(6,28)

The crystal structure of magnesium varies from those of the steels and aluminums, the atoms being arranged in a hexagonal close-packed lattice. The orientation of slip planes within the hexagonal lattice is more restricted than in the

cubic lattices; as a consequence, cold working of magnesium and its alloys is difficult because crystal deformation is directly dependent upon the orientation of slip planes with respect to the direction of working. Especially in sections of small thickness, the preferential crystal deformation which may result from rolling in one direction only will cause wide variations in the properties within the cold worked metal. In practice this problem is overcome by control of heat treatment to prevent excessive grain growth and by changing the direction of rolling to improve the statistical average of crystals deformed in the direction of rolling.(14,24)

Magnesium readily forms a protective oxide coating, and in inland atmospheres the metal and its alloys possess good resistance to corrosion. However, the metal is quite susceptible to the chlorine ion and hence is not well suited for marine applications. Furthermore, as might be surmised from the fact that magnesium is used for sacrificial anodes in cathodic protection systems, the metal deteriorates rapidly when in electrical contact with more noble metals or their salts. For this reason great care must be taken to insulate magnesium from other dissimilar metals.(64)

Magnesium and its alloys have a tensile modulus of elasticity of 6,500,000 psi. Pure magnesium has an annealed tensile strength of 27,000 psi and a yield strength of 14,000 psi; in the hard rolled state these values are

increased to 37,000 psi and 27,000 psi respectively. The metals most commonly alloyed to magnesium are aluminum, manganese, and zinc. The wrought magnesium alloys may attain ultimate strengths as high as 53,000 psi, and yield strengths may increase to as much as 40,000 psi.(5,6)

The wrought alloys may be shaped in a variety of ways. Because of difficulties previously discussed, rolling is generally restricted to plates and sheets, and these forms are usually rolled twice with successive directions of rolling varying 90 degrees. Most other structural shapes are extruded or forged. Because of the excellent extrudability of the magnesium metals, members of very complex cross section may be so formed; structural members as deep as 14 inches have been fabricated by extruding.(4,5,6,28)

In view of the pyrotechnic propensities of magnesium powder and ribbon, misgivings have been expressed as to the practicability of welding magnesium. However, the problem is simply one of heat conductivity, and most fabricated magnesium shapes have sufficient mass to conduct heat rapidly away from the weld area without incendiary effects.(14)

As a material for aircraft construction magnesium has obvious advantages; as a consequence, the greater part of the United States' magnesium production has been utilized directly in the aircraft industry or has been stockpiled for future military use. In structural applications magnesium is well

suited to those special applications which call for fabrication of an unusually complex structural section; however, it is quite unlikely that the metal will seriously challenge steel or aluminum for general structural use.(6,7,49)

The latest of the "wonder metals" and the current press agents' dream is titanium, the new "middle-weight champion" of the metallurgical world. The titanium alloys unquestionably possess excellent mechanical properties; however, the claque usually forgets to mention one of the outstanding characteristics of these metals -- the price. The current price of titanium sheet is about 17 dollars a pound, and wire may run as high as 35 dollars a pound.(29,41)

Actually titanium is not a particularly new discovery. In spite of the comparatively great abundance of the element in the earth's crust, though, the metal is widely dispersed, and there are very few deposits of titanium ores sufficiently rich to justify commercial exploitation. This, coupled with the difficulty of refining the ores, accounts for the high cost.(28)

From the freezing point of 3050°F down to 1620°F, the atoms of pure titanium are oriented in a body-centered cubic lattice; below 1620°F the atomic arrangement is hexagonal close-packed. These phases are respectively designated beta and alpha. The effect of alloying is to lower the temperature at which the beta phase is stable. Titanium alloys may be all

alpha, part alpha and part beta, and all beta. In the all alpha alloys aluminum is the principal alloying constituent; tin may be added as a secondary agent. The alpha-beta alloys contain various proportions and combinations of aluminum, chromium, iron, manganese, molybdenum, and vanadium. The all beta alloys are similar to the alpha-beta alloys except that greater quantities of the alloying elements are added; these beta alloys are still in the laboratory stage of development, and will not be further elaborated. Furthermore, titanium technology is so recently developed that there is as yet no industry-wide standardization of the various alloys.(7,29,40)

From the preceding discussion of magnesium it should be apparent that cold working of the alpha alloys presents difficulties. In the alpha-beta alloys, the workability is improved in direct proportion to the amount of beta phase present. Moreover, strengthening heat treatments are possible with these latter alloys.(29,40,67)

The titanium alloys and the austenitic stainless steels have essentially the same corrosion resistant properties with one notable exception: the titanium alloys possess excellent resistance to the chloride ion and thus are virtually non-corrosive in marine environments.(29,71)

Commercially pure titanium has an ultimate tensile strength of 36,000 psi, and its yield strength is 20,000 psi. The alloys have ultimate strengths to 150,000 psi with yield

strengths as high as 140,000 psi. The outstanding feature of the titanium metals is their strength retention in the temperature range of 300-700°F. With their relatively low specific gravities (4.5 as compared to 8.0 for the 18-8 steels) the titanium alloys have the most favorable strength to weight ratio in this temperature range, and the resultant saving of weight has been sufficient to justify the additional cost of titanium in aircraft construction. Because of the high skin temperatures of modern high speed aircraft (600°F at speed Mach 2 at an altitude of 35,000 feet), titanium is now being used for general air frame construction as well as for engine nacelles.(7,29,41,42,55,56)

An evaluation of the structural potentialities of the stainless steels and light weight metals would be incomplete without some mention of the foreseeable economic futures of each of the metals. In comparison to a price of 4½¢ per pound for mild steel sheet, the per pound prices of sheet of the other metals are; 18-8 stainless steel, 46½¢; 24ST aluminum, 44½¢; magnesium, 36¢; titanium alloy, $17.(29)

The annual production of stainless steel and aluminum now exceeds 1,000,000 tons each, so it is quite unlikely that any immediate price relief is in sight. The cost of stainless steel is largely dependent upon the price of chrome which seems to be in perpetual short supply. Even though the aluminum industry is now much more competitive than was the case

prior to World War II, amortization of plant expansion costs could be expected to offset any reduction of production cost which might accrue from increased production rates.(6,7)

The magnesium industry, stimulated by government assistance and military demands, reached a peak production of 184,000 tons annually during World War II. During the Korean hostilities, production again passed the 100,000 ton mark, but this tonnage was produced only by reopening government-owned plant facilities. At the present time, annual consumption is not expected to exceed 25,000 tons. Thus little reduction in the cost of magnesium alloys can be expected unless peacetime consumption increases drastically.(6,7)

Expansion of the titanium industry is also being assisted considerably by the government. In 1948 the total commercial production was 3 tons; by 1957, production is expected to reach 35,000 tons. However, by the latter year, military requirements for the metals are estimated at approximately 100,000 tons, and it is expected that civilian requirements could equal that amount. Even though the laws of supply and demand will operate to uphold the price of titanium, it is quite possible that the costs may be reduced substantially because of reduced production costs.(7,17,29)

Despite the price picture painted above, a direct comparison of per pound prices does not tell the whole story.As

has been previously pointed out, there are many intangible benefits of the various materials which are difficult to evaluate. Furthermore, in many instances fewer pounds of material may be needed because of higher strengths and/or lower specific gravities than those of the mild steels.

The revision of conventional building design techniques can further reduce the number of pounds of materials required. In lieu of the conventional column, beam, and girder concept, it might prove feasible to adopt some of the features of monocoque construction. In structures of this latter type, the skin and the frame are one, so the technique readily lends itself to materials which are produced in sheet form. By development of this type of construction, the designer can most economically utilize the best properties of the less commonly used structural metals.(50)

Selected Biblicgraphy for more detailed presentation of design information for materials discussed in Chapter II.

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CHAPTER III

STABILIZED SOILS FOR BUILDING CONSTRUCTION

Probably the oldest of structural media is earth -- the annals of paleontology cannot establish when the first insect piled up grains of sand or when the first reptile covered its eggs with mud. Significantly, most human cultures have gone through stages of extensive utilization of earth structures. However, because of its early origins, earth building construction is generally considered too primitive for modern tastes.

Fortunately, the last half century has seen a tremendous increase in the scientific and engineering interest in soils. By painstaking investigation modern researchers have rediscovered and systematized many of the soil data which ancient builders had discovered by instinct and trial and error. Now that it is definitely established that the technology of soils is very profound, it may become more fashionable to utilize this "newly developed" highly complex material in many phases of construction.

By no means are the ancient methods of earth construction lost arts: the sun-dried brick of the Mediterranean regions; the adobe of the Southwestern United States; the wattle and daub of the British Isles; the pise de terre of France; the sod huts of Scotland, Norway, and our own Great Plains -- all

are present-day examples of the retention of time-honored techniques. Nonetheless, these earth building types are suitable for use only in climates similar to those in which they were developed. The problem of modern soil science is to lend sufficient permanence and stability to earth structures so that they may be used under more widely varying climatic conditions.

In the field of soil mechanics great strides have been made in the determination of the properties in situ soils, the improvement of foundations, and the systematizing of construction of earth dams, embankment fills, and the like. Concurrently soil scientists have made significant advances in stabilizing soils for road traffic courses and subgrades. In the hue and cry attending these developments other equally important research has been denied widespread reception among engineers -- investigation of soil as a material for building construction.

To adapt soils to structural use two basic operations are necessary: first the soil must be converted to a form which has the desired strength characteristics and shape required for a specific structural use; secondly, the soil must be treated to retain these properties despite weather and other conditions of use. In actual practice these operations are often combined, but it is more convenient to discuss the rudiments of each separately.

The design of a structural soil mix is really quite similar to proportioning a concrete batch. The basic element of each is a granular skeleton for strength with a suitable binder added for cohesion and retention of shape. If the binder is entirely portland cement, the resulting material is portland cement concrete; when asphalt is used as the binder, alphaltic concrete results. If, on the other hand, the binder is made up of colloidal soil material, the resulting structure is designated as granular stabilized soil. If part of the binder material of a granular stabilized soil is replaced by portland cement or by bituminous materials, the resultant products are respectively known as soil cement and bituminous stabilized soils.(10,34,35,36,52,73)

As is the case with concrete, the most difficult problem in the design of stabilized soil mixes is to provide sufficient binder to fill the voids in the granular skeleton and hold the skeleton together. However, if too much binder is added, contact between the grains of the skeleton will be lost, and the stabilized soil will not have the desired strength. Water must be added to the mix to activate the binder soil and bond it to the granular material. This water causes the colloidal material to swell, and this swelling must be accurately predicted if the proper filling of the skeletal voids is to transpire.(34,35,36)

The principal methods of shaping the soil into usable structural units are ramming and puddling. In either case a form is fabricated to the desired shape. If the soil is to be rammed the mix is usually kept quite dry, with only sufficient water for an adequately bonded stabilized soil of the desired density. This mix is placed in the forms in relatively thin layers, and each successive layer is rammed or tamped to insure proper density. With the puddling process excess water is added to produce a mix similar to wet concrete. The mix is then poured into the forms, and as the excess moisture evaporates, the mix hardens.(47,52)

The forming technique used is dependent upon the requirements of the job. Ramming produces a material of greater density and strength than does puddling. Rammed earth also shrinks less than does puddled earth, so more regular dimensions can be maintained. Finally, the forms may be removed immediately after ramming; so to produce a given number of units in a reasonably short time, fewer forms are required for ramming than for puddling. On the other hand, ramming entails considerably more labor and necessitates more rugged forms than does puddling; also, when using the former technique, much closer control over batching is required.(47,52)

In structural application stabilized soils may be formed monolithically or may be formed into blocks and then layed like more conventional masonry. Again the choice of

construction technique depends upon the exigencies of the situation, but a strong point in favor of using blocks is the fact that curing shrinkage of the blocks may occur before the wall is layed up; thus there is less likelihood of shrinkage cracking in a block wall than in a monolithic wall.(47)

The structural use of granular stabilized soils alone is generally confined to regions of arid climate. If any exposure to weathering conditions is contemplated, steps must be taken to weatherproof this material. The ancient builders of the Near East accomplished this by coating the earth walls with a protective stucco coating or by using bituminous waterproofing coatings and bituminous binders.(28)

Through the ensuing centuries bituminous stabilization techniques have belatedly reached a high state of development. Soil cement technology is also now well advanced. These two stabilization techniques are now being applied to earth building construction, and such terms as "bitudobe," "cemadobe," and "terracrete" are becoming familiar in the literature of the art.

In the proper environment the durability of earth structures is amazing, as the prehistoric pueblos of the Southwest will attest. A comparatively modern testimonial to the ruggedness of rammed earth construction and the weatherproofing effectiveness of a stucco coating is a church on the Hill Crest Plantation, Sumter, South Carolina.

This building, an ante bellum relic of the "Old South," is 105 feet long, 27 feet wide, and the end walls rise 43 feet to the roof finial. The church has withstood several hurricanes, a tornado, and an earthquake.(47)

The foregoing comments serve to indicate that stabilized soils can be reliable materials of construction. However, any discussion of the physical and mechanical properties of these materials must be of an extremely vague and general nature, for there are so many variables in their manufacture.

Depending on the soils and stabilizers used, and the degree of compaction of the medium, the density of stabilized soils may vary in the general range of 90 to 150 pounds per cubic foot. The thermal conductivities of the more dense rammed soils are similar to those of the more conventional masonry materials, while the lighter puddled soils may have insulating values as much as fifty per cent greater than those of the more dense media.(16,37,47)

A wide range of strengths is also possible. The plain granular stabilized soils may have compressive strengths of less than 100 psi, while the high cement content soil-cements may have strengths of 1000 psi and up. The materials are notoriously weak in tension, and any design utilizing stabilized soils should anticipate compressive stresses only.(16,37)

Very little is known of the elastic properties of the stabilized soils, although studies in Germany have indicated that the compressive moduli of elasticity of soil cements vary directly with the cement contents and range from about 500,000 psi to 2,000,000 psi. From a general structural design standpoint, these data are of little consequence, but the information would be very helpful in computing the energy absorbing potentialities of an earth structure which might be located in an area of seismic disturbance or which might be subjected to explosive shocks or bombardment.(54)

In tests of fire resistance, earth walls have withstood flame and temperatures of 1600°F without appreciable damage.(37)

The greatest foes of stabilized soils are moisture, and freezing and thawing. The primary purpose of adding cement, asphalt, and resins to the soil is to increase the resistance to these destructive forces. The strength of the mixture is usually a secondary consideration, for the total structural strength desired is usually attained by using a cross section considerably greater than would be contemplated with a more conventional masonry material. Normally the total cost of the soil used is a relatively minor consideration compared to the cost of the stabilizing additives, so the problem in designing the soil mix is to use as little additive as possible and still keep the dimension of the cross section within manageable limits. The usual minimum thickness for a soil

wall is about a foot, but if the wall is to be quite high or is to support a floor, the thickness may be as much as three feet.(37,47,73,75)

The weight of the wall itself constitutes a considerable portion of the load on an earth wall; consequently, the practical limit on the height of an earth building is one story. If a second floor is desired, it is usually recommended that the superstructure for the second story be of frame construction. Nonetheless, two- and three-story buildings have been built with earth walls right up to the eaves.(47)

From the restrictions on building heights it is apparent that stabilized soil construction is most suitable for those localities in which land utilization is no particular problem. On the other hand, because of the relatively low cost of the material, large living space may be enclosed inside earthen walls at very little expense.(47)

Perhaps the greatest impetus to earth construction has been given in those underdeveloped areas where soil, space, and unskilled labor are plentiful and where the cost of more "civilized" types of construction would not be justified. However, it is interesting to speculate on more urbane uses of the material. As has been previously stated, the structural use of soils makes possible the inexpensive enclosure of elbow room; thus space for gracious living may be purchased at "crackerbox" prices.(37,47)

The use of earth structures for military advanced base construction certainly merits consideration. From a logistics standpoint it seems more feasible to transport a few tons of soil stabilizers than to occupy many bottoms with other building materials. And in an era when a bomb shelter in every back yard may become a reality, the use of soils for this purpose should be well exploited to prevent severe demands on the more common materials of construction, which, in times of emergency, are usually in short supply.

An interesting recent development in the field of maritime construction has been the use of sand asphalt for the construction of beach groins. Although the material does not properly fall within the purview of stabilized soils, the relationship is considered close enough to justify a discussion at this juncture.(9,11)

Essentially a groin is a structure built at an angle to the shore line for the purpose of trapping sand which is carried in the littoral shore currents, thus building up the beach. The location and spacing of groins is a rather complex procedure and will not here be exposed. However, suffice it to remark that unless expensive model studies are made, such location is a rather inexact science, and oftentimes, the designed location may prove to be improper after the groin has been constructed.(22)

Tho most usual matcrial for permanent groin construction in this country is rubble masonry. Unless a quarry is locatod near the construction site, the material may become inordinately expensive. The placing of the stone to insure proper interlock and minimum permeability is also strenuous.(22)

Therefore, any development which could utilize beach sands for such construction seems to offer appreciable economy. Furthermore, the low cost of sand asphalt groins makes possible the erection of test groins at various orientations without great expense.

The actual groin cross section varies to suit the needs, but the design should be aimed at preventing underscour of the structure, and the groin should be carried far enough inland to prevent the possibility of a washout at the inboard end.(9)

Test installations of sand asphalt groins have been constructed at Wrightsville, North Carolina, and Ocean City, Maryland. The material used for the constructions consisted of beach sand and 6-12 per cent asphalt, the higher asphalt contents being at the outer ends of the structures. With the high asphalt contents, the material would have a rather rubbery consistency, and hence the structures would tend to deflect and flow rather than to rupture under wave forces. In the event of severe storms, it is quite probable that the structures would fail, for the material possesses no great

strength. However, repairs to groins of this sort would be quite simple, requiring only the dumping of more of the mixture in the damaged area.(9,27)

The test installations have not been in use long enough to obtain any reliable service data; in all likelihood, the asphaltic structures will prove considerably less durable than those of stone. On the other hand, groins sometimes perform their jobs very rapidly; likewise, the capricious currents seem to go through alternate cycles of scour and deposition, so there is never any guarantee that the groins need be permanent. In any event, construction and replacement costs of sand asphalt groins are small compared to the first cost of masonry groins, so the experiments with the former material may well prove to be the key to inexpensive shoreline preservation.

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CHAPTER IV

STRUCTURAL PLASTICS

The newest group of materials to make their impress upon the field of building construction are the structural plastics. Because of the exigencies of World War II, the childhood and adolescence of the plastics industry were somewhat truncated, and the technology of the materials is now in an advanced, but still progressive state of development.

Perhaps the most confusing characteristic of these materials is their name, for the engineering mind tends to confuse "plastic" with "plasticity." Actually, the former term means that the materials are capable of being molded; in an engineering sense, some of the reinforced plastics are completely elastic to the point of failure.

The varieties of plastic materials are almost as numerous as the uses to which they are put. However, at the present stage of development, the plastics which seem most practicable for structural use are the fiberglass reinforced plastics, hereafter referred to as FRP. These materials, like reinforced concrete, are non-isotropic, two phase substances consisting of fiberglass reinforcement which furnishes most of the strength of the material and a plastic which binds the fibers together and gives the material sufficient rigidity for retention of shape. (62,63)

Several different compositions of glass may be drawn into fibrous form, but the fibers most desirable for high strength structural laminates are those of type "E" glass, a relatively soda-free lime-alumina-borosilicate solution with a specific gravity of 2.55 in the fibrous form. Filaments of less than one-thousandth of an inch in diameter drawn from this glass attain tensile strengths of approximately 400,000 psi. Probably the only metallic filament which can better this performance is finely drawn tungsten which can resist stresses as great as 590,000 psi. (53,63)

Glass fibers are perfectly elastic to rupture with a modulus of elasticity of 10,500,000 psi, and the material exhibits no measurable creep at room temperatures. The static fatigue strength of fiberglass is approximately 50 per cent of the ultimate strength, while the endurance limit is about 25 per cent of the ultimate.(63,70)

Rovings and continuous filament yarns are the forms of fiberglass most used for parallel reinforcing in rods and similar FRP sections. In laminated sheets, however, mats and woven fabrics are generally utilized. Fabrics have marked directional strength characteristics depending upon the orientation of the fibers in the weave; if the woof and the warp are equally heavy, maximum strengths are observed in the directions of the strands, with lesser strengths in intermediate directions. Fabrics with a heavy warp and a light woof are principally used for unidirectional reinforcement. (63)

On the other hand, mats are formed of short pieces of strands which are randomly oriented. Thus mats possess comparatively uniform properties in all directions in the plane of the fabric,although the maximum strength is less than that of a woven fabric with the same glass content. However, mat is appreciably less expensive than woven fabric.(62,63)

Glass fibers have a great surface affinity for water, and are invariably coated with a thin water film. To overcome this tendency and to insure maximum resin-to-glass adhesion, special finishes are applied to fabrics used in high strength laminates.(62,63)

Basically, the plastics utilized in FRP may be categorized as thermosetting or thermoplastic. In the raw state, thermosetting plastics are of a fluid nature; after the addition of heat for a prescribed curing period, these plastics are transformed into their rigid forms. Following curing, subsequent addition of heat will not cause the materials to revert to the plastic state. The thermosetting plastics are predominantly resins and among them are the polyesters, epoxys, phenolics, melamines, and silicones.(25,62,63)

Thermoplastics are those which normally are rigid in form and become plastic upon the addition of heat. From a structural viewpoint, the chief drawback of these materials is the fact that they become plastic whenever heat is applied. The predominant compounds in this plastics category are the polystyrenes and the polyvinyl chlorides.(25,62,63)

Although any of the thermosetting plastics may be used satisfactorily in the manufacture of structural laminates, the most highly developed and most widely used of these resins are the polyesters. Properties of a typical polyester resin are as follows: specific gravity, 1.22; tensile strength, 7500 psi; compressive strength, 22,000 psi; modulus of elasticity, 550,000 psi.(31,63,72)

Polyester resins and fiberglass-polyester laminates possess good resistance to sea water and to most harbor contaminants. In addition, these laminates are essentially proof against marine borers. After four years' exposure, mild attack by marine fungi was noted on test specimens, but the attack did not seem to be progressive; no correlative test data are available to evaluate the structural effect of fungal attack.(19,25,26,59)

Solar radiation has a deleterious effect on polyester laminates, and the resins are also flammable, though slow burning. Researches are in progress to make the materials less photo-susceptible and to render the resins self-extinguishing if not flameproof.(33,62)

It would seem that computing the properties of a resin-fiberglass laminate would merely be a problem of determining the relative amounts of each material in the cross section and then analysing by means of the transformed section. However, because the fibers in the mat or fabric are not

uniformly stressed, the ultimate strengths are considerably less than would be expected. Therefore, it is first necessary to obtain strength data for the particular glass fabric used; then analysis may proceed as outlined above.(63)

Properties of FRP laminates are also affected by the method of fabrication. The simplest process is the contact or no-pressure method. In this system of manufacture a single mold, either male or female, is used. The glass reinforcing is shaped to the mold, the fluid resin is applied by hand, and the article is cured in the mold. By this method of fabrication, laminates with relatively poor physical properties are formed, for excess amounts of resin are needed to insure that the reinforcement is adequately impregnated. Nevertheless, because of the comparatively low cost of this method of manufacture, pre-production prototypes are usually constructed in this manner.(62,63)

Another inexpensive method of prototype production is the vacuum or pressure intrusion system. With this process matched molds are made with a predetermined clearance between them. After the reinforcing is placed, the resin is introduced into the mold either by drawing a vacuum in the mold cavity or by forcing the fluid resin into the mold under pressure. The resulting laminates have properties only slightly better than those obtained by contact molding.(62,63)

For production runs, particularly if large items are to be fabricated, or if the molded product contains complex

reverse curves, the vacuum or pressure bag processes are adopted. With these methods only a single mold is utilized; a flexible membrane is then tailored to conform to the shape of the mold. After the glass and resin are layed up on the mold, the membrane is forced tightly over the mold, either by drawing a vacuum from within or by applying pressure from without.(62,63)

For quantity manufacture of closely controlled products, matched dies are used. After the plastic and reinforcement are introduced into one of the dies, the two parts are forced together to a controlled clearance by a predetermined pressure. By this method high quality laminates with uniform properties are reasonably insured.(62,63)

The fabrication process used, and thus the quality of product which may result, is largely dependent upon the number of items to be produced. Logically, expensive dies cannot be justified for test prototypes. Consequently, these prototypes are usually assembled by one of the processes which produces relatively poor laminates. This should be taken into account when evaluating test assemblies lest the product be judged too harshly.

From the foregoing discussion it is apparent that laminates may be designed to give almost any desired performance. Typical properties of a mat reinforced polyester containing 48 per cent glass and laminated at 25 psi are:

tensile and compressive strengths, 20,000 psi; modulus of elasticity, 1,200,000 psi; specific gravity, 1.55. With parallel strand reinforcing and higher glass contents, tensile strengths greater than 100,000 psi may be obtained. (31,72)

As temperature decreases, the strength of FRP increases without accompanying embrittlement. The ordinary glass-polyester laminates retain their strengths up to about 250°F, but special resins have been developed for service at temperatures up to 550°F. With a density close to that of magnesium, FRP already has limited applications in aircraft construction; the development of temperature resistant laminates may make the material a rival of titanium for use in airframes of supersonic aircraft.(18,44,63)

FRP laminates are priced in the range of 50¢ to $1.00 per pound, depending upon the amount and type of glass reinforcing and the quality of resins and finishes used. However, fabrication costs are usually low compared to processing costs for other materials, and if complex sections are to be formed, it may in the end be cheaper to use plastics because of the reduced labor costs.(63)

In structural applications, use of FRP laminates is somewhat restricted by the fact that there are few suitable methods of joining plastic sections; bolting is the most dependable practice, although research is in progress for the development of trustworthy resinous cements. Nontheless, the laminates are being used for fuel and chemical storage

tanks of appreciable capacity. The increase in the production of plastic boats attests to the serviceability of the material in marine environments.(30,58,72)

Because color may be molded into resins, FRP is gaining popularity for decorative architectural uses, and the material is available in a variety of corrugated and sandwich type building panels. Furthermore, laminates may be made translucent or transparent if desired, and skylights and monitor windows are among the new applications of the material.(45)

Ten years ago plastics were generally regarded as substitute materials to be tolerated until wartime shortages of the more usual materials were overcome. However, by continuing research and development, the plastics industry has created a definite niche for its products, and the full potentialities of FRP as a structural medium have yet to be realized.

Recommended Supplementary Reading

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CHAPTER V

DESIGN OF A LIGHTWEIGHT PONTOON STRUCTURE

One of the Seabees' most versatile structural elements is the Navy Lightered (N.L.) pontoon. Much of the cargo landed at beachheads in support of military operations has been transported ashore over floating causeways constructed of N.L. pontoons. Self-propelled barges, floating piers, crane barges, and floating drydocks are among other structures which may be fabricated from pontoon assemblies. Strings of pontoons have been used as simply supported bridge spans, although such service is not recommended practice.(21)

Basically the N.L. pontoon is a 5' x 5' x 7' steel box; the skin of the box is 3/16" mild steel plate, and the structure is heavily braced internally with 12-inch junior beams split into T-sections. The individual pontoons, weighing 2000 pounds each, are assembled into longitudinal strings by means of four heavy continuous angles which are rigidly bolted to the corners of the pontoons. If a structural width of more than 7 feet is desired, two or more strings can be joined side by side.(21)

Deck loads are imposed directly upon the pontoons, and these elements transmit the loads to the angles and resist all horizontal shearing forces. The angles resist tensile and

compressive bending stresses of the structure as a whole, and must resist vertical shears as well. A 55-foot pontoon string simply supportedat the ends has successfully carried a concentrated static load of 60 tons at the center of the span.(21)

Because N.L. pontoons are of all steel construction, various fittings and appurtenances may be welded at almost any location on the structure; this further adds to the versatility of these floating erector sets. Moreover, the pontoons are designed with connections for flooding and pumping in case a submersible structure is desired.(21)

Despite the many virtues of N.L. pontoons, the units have several drawbacks. In the first place, the individual pontoons are heavy, and lifting tackle is necessary for handling and assembly. In addition, when the units are shipped, one pontoon occupies about 4 measurement tons of cargo space. A further shortcoming is the mild steel skin which deteriorates rapidly unless the structures are constantly maintained; as a consequence, the service life of pontoon assemblies is usually very short.

In view of the foregoing, it seems practicable to investigate the potentialities of some of the newer structural materials for use in pontoon structures.

Before proceeding with any design computations, it is first necessary to establish the criteria which the finished

assembly should satisfy. Because the design of special purpose barges and submersible structures requires extensive detailed study, the basic design herein considered will be confined to pontoons and decking for causeways and landing stages.

In order to keep the pontoon free of excessive internal bracing, the total buoyancy of the submerged pontoon will be limited to about one ton. The deck system will be designed to support a hypothetical 4-wheeled vehicle with one ton wheel loads at a tire pressure of 50 psi. The pontoons will be designed to transmit buoyant forces only. All loading moments and shears will be resisted by the deck system.

From the criteria imposed, FRP seems a logical choice of material for the pontoons, for a structurally efficient shape can be easily fabricated from this material. Spherical pontoons would seem to require the least material for a given displacement, but special spherical bearing seats would be necessary to prevent high contact pressures between pontoon and deck. A cylindrical shape is also economical in use of material, and the flat, circular ends would provide good bearing between the deck and the float. However, a certain amount of draft or taper is necessary on the sides of molded laminates to facilitate removal of the molded part from the dies. Moreover, if a conical section is used, the individual pontoons would nest into each other, reducing space required for storage.

From the foregoing considerations is evolved the concept of a pontoon made up of two identical truncated cones resembling peach baskets, which would have, in place of the basket rim, a flange. The two halves would then be connected at the flanges by a bolted joint made water tight by a gasket. When the pontoons were not in use, the halves could be nested and stacked.

The deck would be of sandwich panel construction with a honeycomb core for lightness. On the under side of the panels would be projecting lugs arranged in circular patterns to position the pontoons with respect to the decking, although no positive connection between pontoon and deck would exist. To prevent the floats from bobbing out of position, another, lighter panel section with positioning lugs on its upper surface would be located underneath the pontoons and would be connected to the decking by struts equal in length to the depth of the pontoons. The struts would not be calculated to transmit loading stresses to the bottom panel but would be rigid enough to resist the shock of beaching the causeway and to prevent damage to the structure during launching.

The pontoon will be designed to resist stresses due to buoyant uplift or due to submergence to 10 feet, whichever are greater. In the ensuing calculations, the density of sea water, γ, will be assumed to be 65 lb/cuft, and the Poisson's ratio, μ, will be assumed as 0.25.

Use a trial section (half of assembled pontoon) with radii of 18" and 21" and a height of 24"; then:

Volume of pontoon

$$V = 2\pi \frac{h}{3}(R^2+Rr+r^2)$$

$$= \frac{2\pi(24)}{3(1728)}(324+378+441) = 33.2 \text{ cuft}$$

Buoyancy at submergence

$$P = V\gamma = 33.2(65) = 2160 \text{ lb}$$

Buoyant pressure

$$p = P \div \pi R^2 = \frac{2160}{324\pi} = 2.12 \text{ psi}$$

Pressure at -10 feet

$$p = \frac{10(65)}{144} = 4.5 \text{ psi -- use this pressure.}$$

If the plane surface of the section is assumed to be a circular plate with fixed edges, then:

Maximum moment at edge

$$M_R = -\frac{pR^2}{8} = -\frac{4.5(324)}{8} = -183 \text{ in-lb/in} \qquad (65)$$

Moment at center

$$M_o = \frac{1+\mu}{16}(pR^2) = \frac{(1.0+0.5)}{16}4.5(324) = 138 \text{ in-lb/in} \qquad (65)$$

If the surface is considered to be a circular plate simply supported at the edges:

$$M_o = \frac{3+\mu}{16}(pR^2) = \frac{3.5}{16}(4.5)324 = 320 \text{ in-lb/in} \qquad (65)$$

Actually the edge restraint is intermediate between fixity and freedom, and the assumed μ is probably a little high; so the maximum design moment will arbitrarily be taken as 300 in-lb/in.

Draft of the side walls is so slight that lateral pressures will be assumed to create compressive stresses on vertical sections only. It will further be considered that the planar surfaces do not resist lateral pressures.

Maximum compressive force

$$C = \frac{2rp}{2} = 21(4.5) = 95 \text{ lb/in}$$

Vertical forces tend to cause buckling of the side walls. No data are available on the buckling of plastic cylinders so the walls will be analysed as a 24" plate loaded in the plane of the plate.

Maximum buckling force

$$F = \frac{\pi R^2 p}{2\pi R} = \frac{324(4.5)}{2(18)} = 40.5 \text{ lb/in}$$

This force is equivalent to a force of 162 lb/in if the unsupported length is reduced to 12". However, it is assumed that the walls have total fixity at the flange, so the value of buckling force to be considered is 81 lb/in for an unsupported length of 12".

After consulting the Heyser charts for mat reinforced laminates, it is noted that the maximum requirement is that for bending. Thus the laminate selected is a mat reinforced polyester resin one quarter of an inch thick containing 50 per cent by weight of glass. The material weighs 2.1 pounds per square foot, and is priced at $1.10 per square foot (52-1/2 cents per pound).(63) The surface area of the pontoon is approximately 57 square feet, so the weight of the

plastic portions is 120 pounds. The material cost would be \$62.50, and with a liberal allowance for the cost of bolts, gasket, and molding, the entire pontoon should not cost more than \$75 if produced in quantity.

The design of the decking presents a slightly different problem of analysis. The core of a sandwich panel is not considered to resist bending, but by horizontal shear transmits bending strains between the facings. The core also resists compressive forces and vertical shear.

Quite a number of materials may be used for the facings and the cores of the panels. However, to be consistent with the concept of light weight, corrosion resisting construction, FRP facings and an aluminum honeycomb core will be utilized.

For a trial section, the facings will be the same quarter-inch laminate used in the pontoons, and the 3-inch core will be an aluminum honeycomb with 95 per cent voids in the cellular structure.

The most conservative analysis of the bending strength of the decking would be to consider a 1-foot strip subjected to unidirectional bending.

Moment of inertia of the section

$$I = \frac{bt_f(t-t_f)^2}{2} \qquad (63)$$

b = width of section
t = total thickness of panel
t_f = thickness of facing (two faces)

$$= \frac{12(0.5)(3.5-0.5)^2}{2} = 27 \text{ in}^4$$

The maximum allowable stress in the laminate is 20,000 psi. Thus the maximum moment which may be resisted is:

$$M = \frac{fI}{y} = \frac{20,000(27)}{1.75} = 310,000 \text{ in-lb/ft}$$
$$= 12.9 \text{ ft-ton/ft}$$

This is tantamount to carrying a 5.1 ton concentrated load at the center of a 10 foot span.

If the allowable tensile and compressive stresses in the aluminum are 20,000 psi, the bearing strength of the core is:

$$C = 0.05(20,000) = 1000 \text{ psi}$$

Considering an allowable shear stress of 12,000 psi in the core, the resistance to vertical shear in a 1-foot cross section is:

$$V = 0.05(3)12(12,000) = 21,600 \text{ lb/ft}$$

Maximum permissible horizontal shear stress

$$H = 0.05(12,000) = 600 \text{ psi}$$

From the foregoing computations it is quite apparent that the selected deck section appreciably exceeds the original design criteria. However, the excess strength serves several useful functions which would be difficult to consider precisely in the design. In the first place, impact stresses are always uncertain, and reinforced plastics do not possess the ability of more ductile materials to absorb large quantities of energy by plastic deformation; they either deform elastically or rupture. Therefore, a little extra strength

in the decking makes the structure more resistant to rough treatment. Secondly, the extra strength means extra stiffness and consequent distribution of loads over a wider area. Practically speaking, this implies that more pontoons will be utilized to carry any given load; consequently, depth of immersion under the load will be less than would normally be anticipated, and the deck level will not fluctuate too markedly as moving loads traverse the causeway.

The decking thus designed would have a weight of about 6.3 pounds per square foot, and when fabricated would probably cost in the neighborhood of $6.00 per square foot.

The bottom paneling and its connecting struts will not be considered in this discussion; nor will such details as flange bolts and gaskets, connections for adjacent deck sections, and deck fittings be treated herein. These items would best be resolved by service testing of prototypes.

A convenient arrangement of the elements as designed would be to have 8' x 8' deck panels supported by four pontoons arranged in a rectangle on 4-foot centers. With such a unit, each component could be handled by two men. Furthermore, there would be no problem of orienting adjacent units, and the dimensions of the entire structure could easily be extended in any direction.

The individual 8'x 8' units would have a capacity of about four tons and would probably cost about $800. A standard

N.L. pontoon section of comparable deck space would weigh 4 times as much but would probably cost only half as much and would have twice the capacity. However,the factors of portability, durability, reduction of maintenance, and ease of assembly offset the price disparity somewhat. From a standpoint of logistics, the advantage definitely goes to the lightweight assembly, for the components could be transported to the scene of operations conveniently stored in the knocked down state; the causeways could then be easily assembled aboard the transporting vessel without the need of special weight handling and welding equipment.

In any event, the cost of constructing a prototype assembly (probably 4-5 times the cost of the production model) could be justified by the lessons which could be learned from the performance and handling characteristics of modular lightweight units even if the design concept proved impracticable for service use.

APPENDIX A

THE GALVANIC SERIES FOR COMMERCIAL METALS IN SEA WATER*

Anodic end

Magnesium and its alloys
Zinc and zinc-coated parts
Aluminum and aluminum alloys
Mild steel
Wrought steel
Cast iron
Stainless steel (18-8) (active)
Lead
Tin
Muntz metal
Nickel (active)
Admiralty brass
Copper
Nickel (passive)
Titanium and its alloys
Silver
Stainless steel (18-8) (passive)

Cathodic end

* Adapted from LaQue(64) and Williams(71)

If two of the metals listed above are in electrical contact in sea water, the material higher on the list will corrode. Note that at the two extremes of the series are the highly anodic magnesium and aluminum alloys and the very inert titanium alloys and passivated stainless steels.

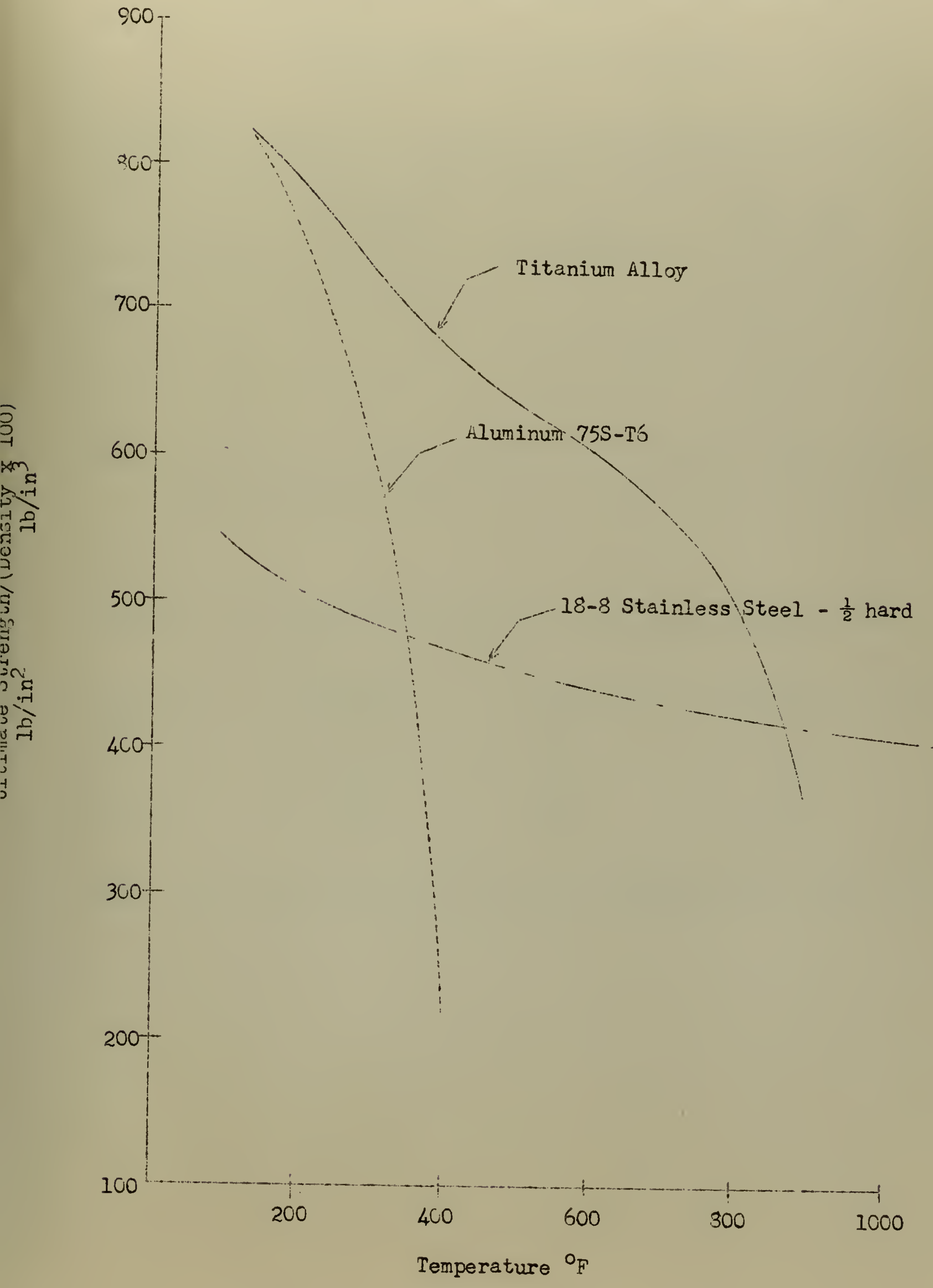
APPENDIX B

PROPERTIES OF STRUCTURAL METALS

Figure B-1. Elastic Properties of Alloys

Alloy	Specific Gravity	E psi x 10^6	G psi x 10^6	Poisson's Ratio	Ultimate Tensile Strength psi x 10^3	Yield Strength psi x 10^3	Elongation %
Aluminum - 17S							
Annealed	2.79	10.4	3.85	0.33	26	10	22
Solution heat treated					62	40	22
Magnesium - AZ31X							
Annealed	1.78	6.5	2.4	0.35	37	22	21
Hard rolled					42	33	11
Stainless Steel - 18-8 Type 301							
Annealed	7.95	28.0	12.5	0.28	105	40	68
Cold worked		25.0	11.0		225	200	7
Structural steel - SAE 1020							
Hot rolled	7.85	29.0	12.5	0.28	55	30	25
Cold drawn					61	51	15
Titanium - AMS4925	4.5	16.5			150	135	18

Figure B-2. Comparative Strengths for Equal Weights of Various Alloys at Elevated Temperatures (After Kostoch - 41)



APPENDIX C

PROPERTIES OF STRUCTURAL SOILS

Figure C-1. Effect of Addition of Stabilizers on Strength of Rammed Earth (After Marini - 37)

Stabilizer	Immediate Strength	7 - Day Strength	28 - Day Strength
None	2.3 kg/cm^2		11.5 kg/cm^2
Lime Mortar	1.3 "	11.2 kg/cm^2	15.6 "
Cement Mortar	1.6 "	12.8 "	21.0 "

Note: Untreated soil was composed of 70% sand, 30% clay; on stabilizing, 100 kg of mortar were added to each cubic meter of soil.

Figure C-2. Comparison of Rammed and Puddled Soil Cement Bricks (After Biggs and Causing - 16)

Method of Forming	Density lb/cuft	Compressive Strength - Pounds Flat	On Edge
Puddling	128	1660	318
Ramming	134	2200	1013

Note: Tests performed on 10" x 10" x 3½" bricks stabilized with 10% by weight of portland cement.

Figure C-3. Elastic Properties of Soil Cements
(After Reinhold - 54)

Soil	Cement:Soil	E - psi x 10^6	Poisson's Number*
100% sand	1:6	1.92	8.35
	1:8	1.56	7.25
	1:10	1.26	7.05
75% sand - 25% clay	1:6	2.00	8.00
	1:8	1.58	7.50
	1:10	1.29	7.35
50% sand - 50% clay	1:6	1.29	9.00
	1:8	1.16	7.75
	1:10	0.92	10.56
100% clay	1:6	0.64	11.10
	1:8	0.53	14.30
	1:10	0.21	18.75

* Poisson's number is the reciprocal of Poisson's ratio.

Note: Modulus of elasticity is based on a tangent to the stress-strain curve at a stress of one-third the ultimate.

APPENDIX D

DESIGN CHARTS FOR FRP MAT LAMINATES
(After Heyser - 63)

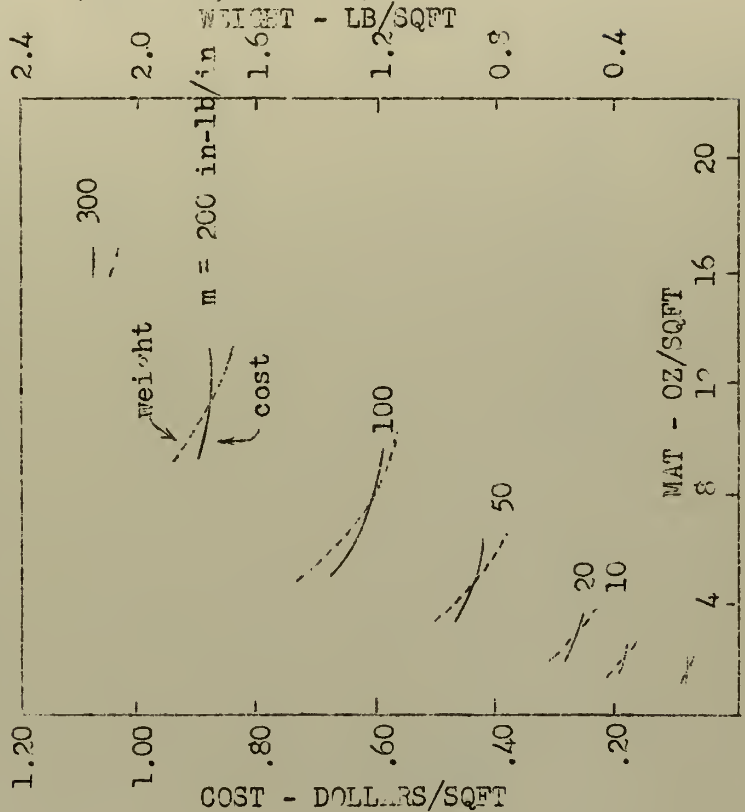


Figure D-2

CURVES OF CONSTANT FLEXURAL STRENGTH

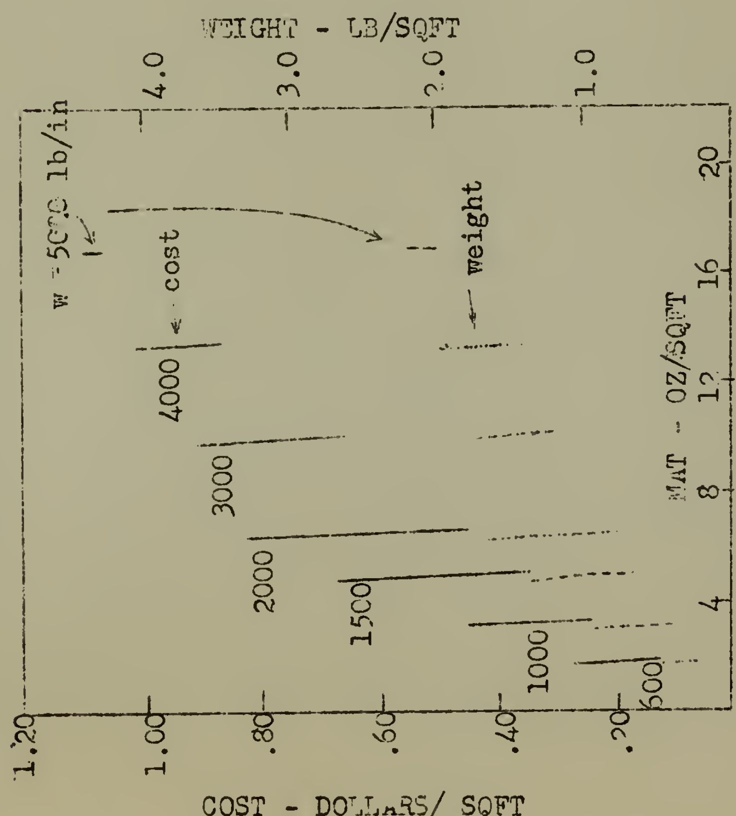


Figure D-1

CURVES OF CONSTANT TENSILE STRENGTH

Figure D-3

CURVES OF CONSTANT COMPRESSIVE STRENGTH

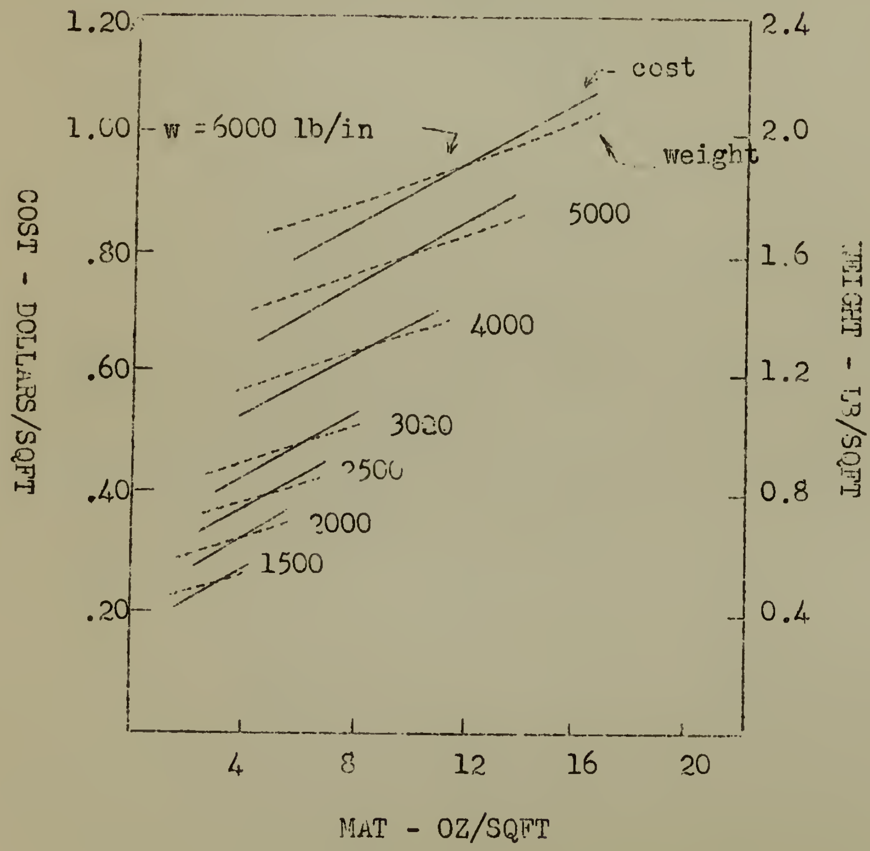
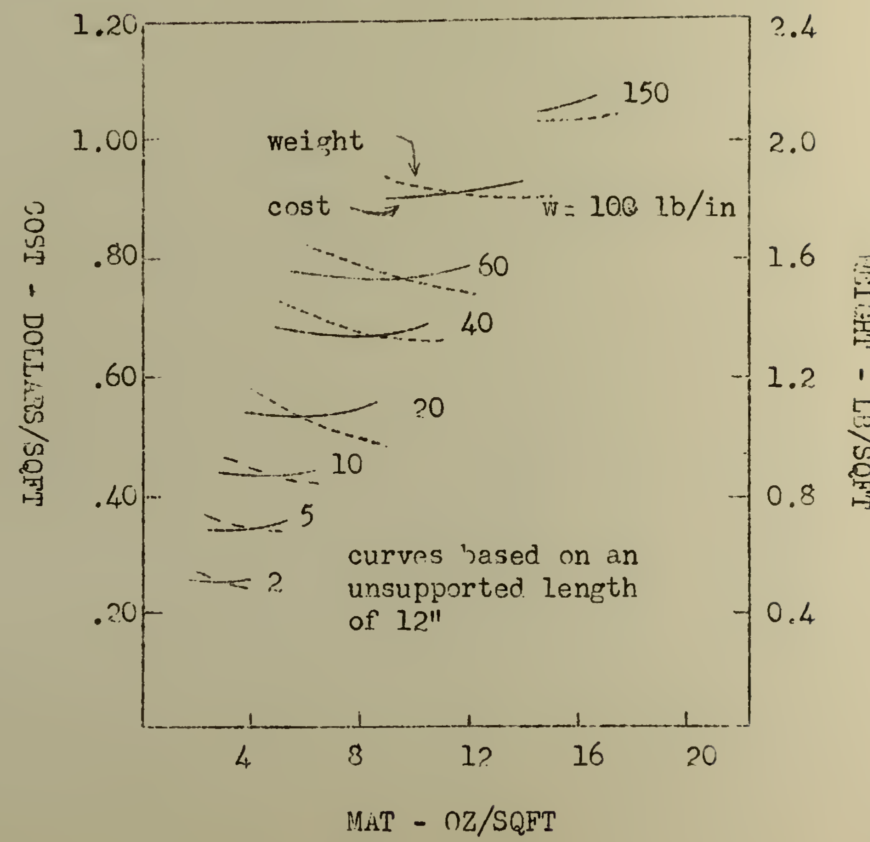


Figure D-4

CURVES OF CONSTANT BUCKLING STRENGTH



APPENDIX E

SKETCHES OF LIGHTWEIGHT PONTOON ASSEMBLY

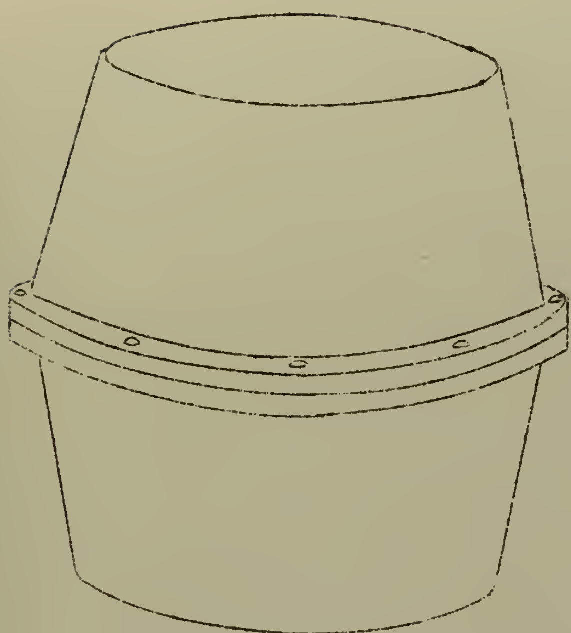


Figure E-1.

Assembled Pontoon

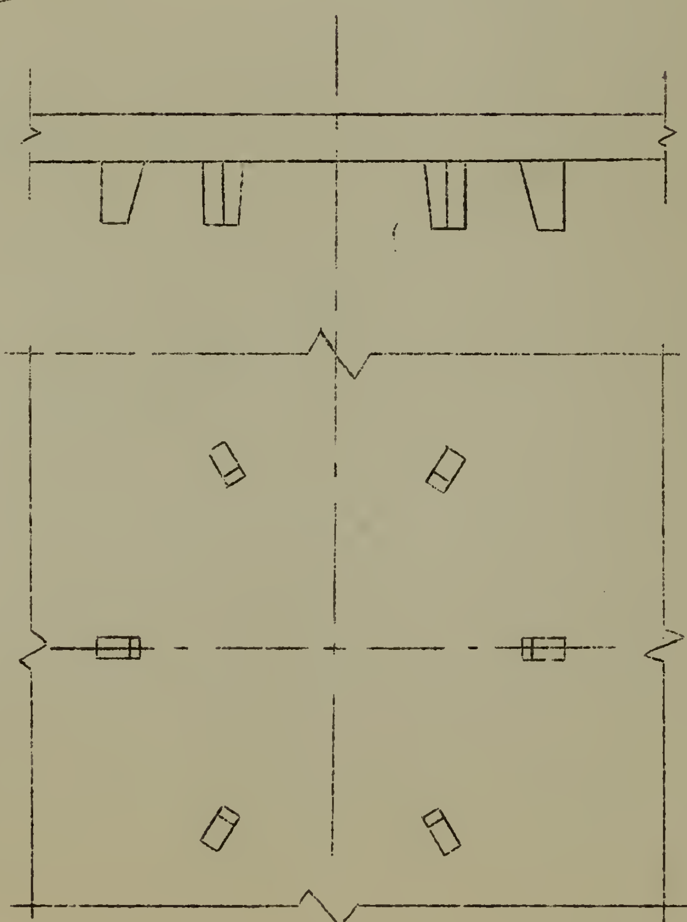
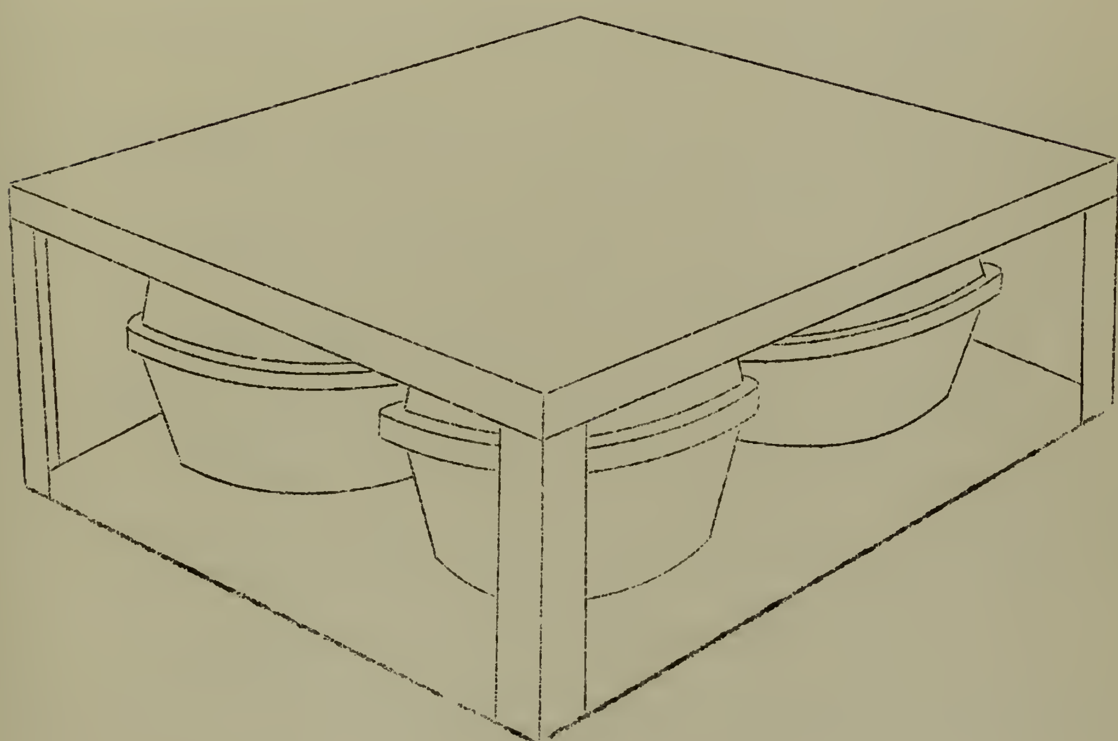


Figure E-2

Side and bottom views of a portion of the deck panel showing detail of pontoon positioning lugs

Figure E-3. Assembled 8' x 8' Causeway Section



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